

# Search for the $\eta$ -mesic bound states with the WASA-at-COSY detector

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**Abstract.** The experiments dedicated to the search for  $\eta$ -mesic Helium were performed with high statistics using WASA detection setups installed at the COSY accelerator in the Research Center Juelich. The search for the  $\eta$ -mesic bound states is conducted via the measurement of the excitation function for selected decay channels of the He- $\eta$  systems using unique ramped beam technique. This report presents recent status of the data analysis.

## 1 Introduction

The mesic nuclei issue currently attracts much interest in nuclear and hadronic physics, both from experimental [1–7] and theoretical points of view [8–27]. Although, this exotic nuclear matter consisting of a nucleus bound via the strong interaction with a neutral meson ( $\eta$ ,  $\eta'$ ,  $K$  or  $\omega$ ) has been predicted over thirty years ago [28, 29], its existence remains unconfirmed experimentally. One of the most promising candidates for the creation of the mesic nucleus is the  $\eta$  meson whose interaction with nucleons is stronger than other mesons [30, 31]. Current investigations of hadron- and photon-induced production of the  $\eta$  meson deliver a wide range of  $\eta N$  scattering length values ( $a_{\eta N}$ ) indicating the  $\eta$ -nucleon interaction to be strong enough to create light  $\eta$ -mesic nuclei [9–12, 32–34]. However, despite many experiments performed, there is still no clear evidence of their existence [35–42]. The interested reader can find recent reviews on the  $\eta$  mesic bound state searches in Refs [6, 7, 16, 18, 30, 45–49].

Some of the promising experiments related to  $\eta$ -mesic Helium nuclei have been performed with the COSY facility [50]. COSY-11 group carried out measurements to search for  ${}^3\text{He}$ - $\eta$  bound states in  $dp \rightarrow ppp\pi^-$  and  $dp \rightarrow {}^3\text{He}\pi^0$  reactions. Excitation functions determined in the vicinity of the production threshold allowed to establish the upper limits of the total cross section to about 270 nb and 70 nb, respectively [51, 52]. The search for  ${}^4\text{He}$ - $\eta$  and  ${}^3\text{He}$ - $\eta$  mesic nuclei has been recently performed by WASA-at-COSY Collaboration in  $dd$  and  $pd$  collisions, respectively. This paper focuses on the results obtained for the search for  $\eta$ -mesic  ${}^4\text{He}$  in  $dd \rightarrow {}^3\text{He}n\pi^0$  and  $dd \rightarrow {}^3\text{He}p\pi^-$  processes [1–4]. The analysis related to  ${}^3\text{He}$ - $\eta$  bound state is in progress [53].

## 2 Search for the $\eta$ -mesic ${}^4\text{He}$

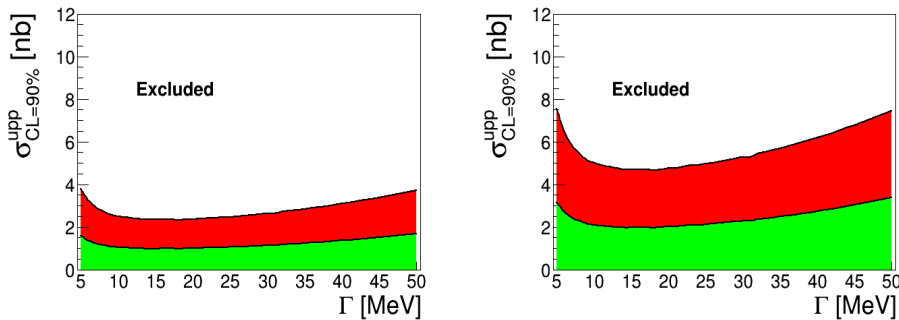
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Measurements with the WASA-at-COSY detection setup dedicated to search for  $\eta$ -mesic  ${}^4\text{He}$  nuclei were carried out twice (in 2008 and 2010) using the unique ramped beam technique which allows for the beam momentum to be changed slowly and continuously around the  $\eta$  production threshold in each of the acceleration cycles [1, 4, 47, 49]. The advantage of this technique is the reduction of systematic uncertainties with respect to separate runs at fixed beam energies [4, 38].

The search for  ${}^4\text{He}$ - $\eta$  bound states was carried out by studying the excitation functions for  $dd \rightarrow {}^3\text{He}p\pi^-$  [1–4] and  $dd \rightarrow {}^3\text{He}n\pi^0$  [1–3] reactions near the  ${}^4\text{He}\eta$  production threshold. A detailed description of the data analysis and simulations leading to determination of the excitation functions is presented in the Refs [1, 4]. Since the obtained excitation functions do not reveal any direct narrow structure below the  $\eta$  production threshold, which could be considered as a signature of the bound state, the upper limit of the total cross section for the  $\eta$ -mesic  ${}^4\text{He}$  formation was determined at the 90% confidence level. For this purpose the excitation curves were fitted simultaneously using the Breit-Wigner function (signal) with a fixed binding energy and width combined with a second order polynomial (background) taking into account the isospin relation between  $n\pi^0$  and  $p\pi^-$  pairs.

In case of the  $dd \rightarrow ({}^4\text{He}-\eta)_{\text{bound}} \rightarrow {}^3\text{He}n\pi^0$  process, the upper limit was for the first time obtained experimentally and varies in the range from 2.5 to 3.5 nb. For the  $dd \rightarrow ({}^4\text{He}-\eta)_{\text{bound}} \rightarrow {}^3\text{He}p\pi^-$  reaction we achieved a sensitivity of the cross section of about 6 nb [1] which is about four times better in comparison with the result obtained in the previous experiment [4]. The obtained upper limits as a function of the bound state width are presented for both of the studied reactions in Fig. 1.

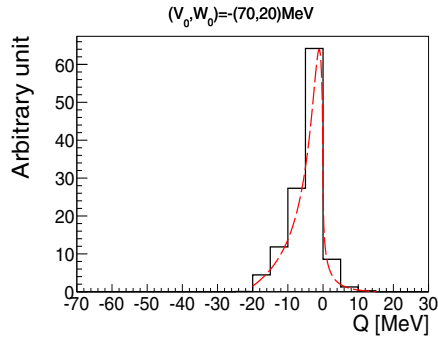


**Figure 1.** Upper limit of the total cross-section for  $dd \rightarrow ({}^4\text{He}-\eta)_{\text{bound}} \rightarrow {}^3\text{He}n\pi^0$  (left panel) and  $dd \rightarrow ({}^4\text{He}-\eta)_{\text{bound}} \rightarrow {}^3\text{He}p\pi^-$  (right panel) reaction as a function of the width of the bound state. The binding energy was fixed to 30 MeV. The upper limit was determined via the simultaneous fit for both channels. The green area denotes the systematic uncertainties. The figures are adopted from [1].

## 2.1 Constraining the optical potential

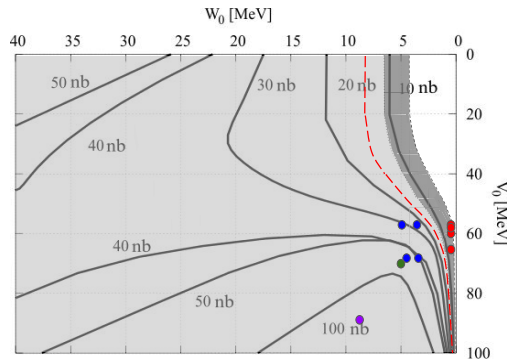
Previously, the data analyses were carried out assuming that the signal from the bound state is described by a Breit-Wigner shape with fixed binding energy and width [1, 4], since there were no theoretical predictions for the  $dd \rightarrow ({}^4\text{He}-\eta)_{\text{bound}} \rightarrow {}^3\text{He}N\pi$  reactions cross sections below the  $\eta$  production threshold. However, at present, a theoretical description of the cross sections in the excess energy range relevant to the  $\eta$ -mesic nuclear search was proposed in Ref. [8]. The authors used a phenomenological approach with an optical potential for the  $\eta$ - ${}^4\text{He}$  interaction and determine the total cross sections for a broad range of real ( $V_0$ ) and imaginary ( $W_0$ ) parameters.

Fitting the theoretical spectra convoluted with the experimental resolution of the excess energy (example Fig. 2) to experimental data collected by WASA-at-COSY [1] brought the upper limit of the total cross section (CL=90%) for creation of  $\eta$ -mesic nuclei via the  $dd \rightarrow {}^3\text{He}N\pi$  process varying from about 5.2 nb to about 7.5 nb.



**Figure 2.** Cross section of the  $dd \rightarrow ({}^4\text{He}-\eta)_{\text{bound}} \rightarrow {}^3\text{He}N\pi$  reaction for the formation of the  ${}^4\text{He}-\eta$  bound system calculated for  $\eta$ - ${}^4\text{He}$  optical potential parameters  $(V_0, W_0) = (-70, 20)$  MeV, plotted as a function of the excess energy  $Q$ . The red dashed line shows the theoretical spectrum while the black solid line shows the convoluted spectrum. Figure is adopted from Ref. [2].

A comparison of the determined upper limits with the cross sections obtained in Ref. [8] made it possible to put a constraint on the  $\eta$ - ${}^4\text{He}$  optical potential parameters. As it is presented in Fig. 3, only extremely narrow and loosely bound states are allowed within the model [8]. A detailed description of performed studies interested reader can find in Ref. [2].



**Figure 3.** Contour plot of the theoretically determined conversion cross section in the  $V_0 - W_0$  plane [8]. The light shaded area shows the region excluded by our analysis, while the dark shaded area denotes the systematic uncertainty of the  $\sigma_{\text{upp}}^{\text{CL}=90\%}$ . The red line extends the allowed region based on a new estimate of errors (see text for details). Dots correspond to the optical potential parameters corresponding to the predicted  $\eta$ -mesic  ${}^4\text{He}$  states. Figure is adopted from Ref. [2].

### 3 Summary and perspectives

Experiments dedicated to the search for  $\eta$ -mesic  $^4\text{He}$  in  $dd \rightarrow ^3\text{He}n\pi^0$  and  $dd \rightarrow ^3\text{He}p\pi^-$  reactions performed with the WASA-at-COSY detection setup did not enable the observation of the resonance structure related to the bound state. However, the upper limits of the total cross sections for  $\eta$ -mesic nuclei formation and decay were determined to be of the order of a few nb [1, 4]. Moreover, a comparison between the phenomenological model proposed in Ref. [8] and experimental data allowed, for the first time, to constrain the range of the  $\eta$ - $^4\text{He}$  optical potential parameters [2].

Recently, the WASA-at-COSY Collaboration has performed a promising experiment dedicated to the search for  $\eta$ -mesic  $^3\text{He}$  in three different mechanisms: (i) absorption of the  $\eta$  meson by one of the nucleons, which subsequently decays into  $N^*\pi$  pair e.g.:  $pd \rightarrow (^3\text{He}-\eta)_{\text{bound}} \rightarrow ppp\pi^-$ , (ii)  $\eta$ -meson decay while it is still "orbiting" around a nucleus e.g.:  $pd \rightarrow (^3\text{He}-\eta)_{\text{bound}} \rightarrow ^3\text{He}2\gamma$  reactions and (iii)  $\eta$  meson absorption by few nucleons e.g.:  $pd \rightarrow (^3\text{He}-\eta)_{\text{bound}} \rightarrow ppn$ . The measurement with a high average luminosity ( $3 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ ) allowed the collection of the largest data sample, in the world available up to now, for  $^3\text{He}-\eta$  [53–55]. The analysis is still in progress and the estimated upper limit value for  $pd \rightarrow ^3\text{He}2\gamma$  and  $pd \rightarrow ^3\text{He}6\gamma$  channels is on the level of a few nanobarns.

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